

# **Shallow Water Fluctuations and Communications**

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## **LONG TERM GOALS**

The central effort of this research will be the development of robust algorithms for reliable, high data rate, acoustic communications in a dynamic ocean environment and demonstration of their use with data collected in a shallow water environment.

## **OBJECTIVE**

We will study shallow water fluctuation physics and the enhancement of performance of broad area acoustic communications in shallow water by building on developments in adaptive channel equalizers in conjunction with the time reversal approach.

## **APPROACH**

Time reversal communications exploits spatial diversity to achieve spatial and temporal focusing in complex ocean environments. Spatial diversity easily can be provided by a vertical array in a waveguide. Alternatively, spatial diversity can be obtained from a virtual horizontal array generated by two elements, a transmitter and a receiver, due to relative motion between them, referred to as a synthetic aperture. In this case, the same data is transmitted periodically. The cost is a reduction in the overall data rate by the number of transmissions accumulated in generation of synthetic aperture. In addition, Doppler compensation is required involving Doppler shift estimation and re-sampling of the broadband communication signal.

Recently we have investigated the feasibility of synthetic aperture communications (SAC) in shallow water [1]. In that work, simple on/off keying modulation was employed to minimize the complexity and not require coherent demodulation. Furthermore, the motion was almost transversal resulting in a small Doppler shift. In this case diversity appears to come from the data being collected in an azimuthally inhomogeneous environment coupled with temporal channel variation between transmissions.

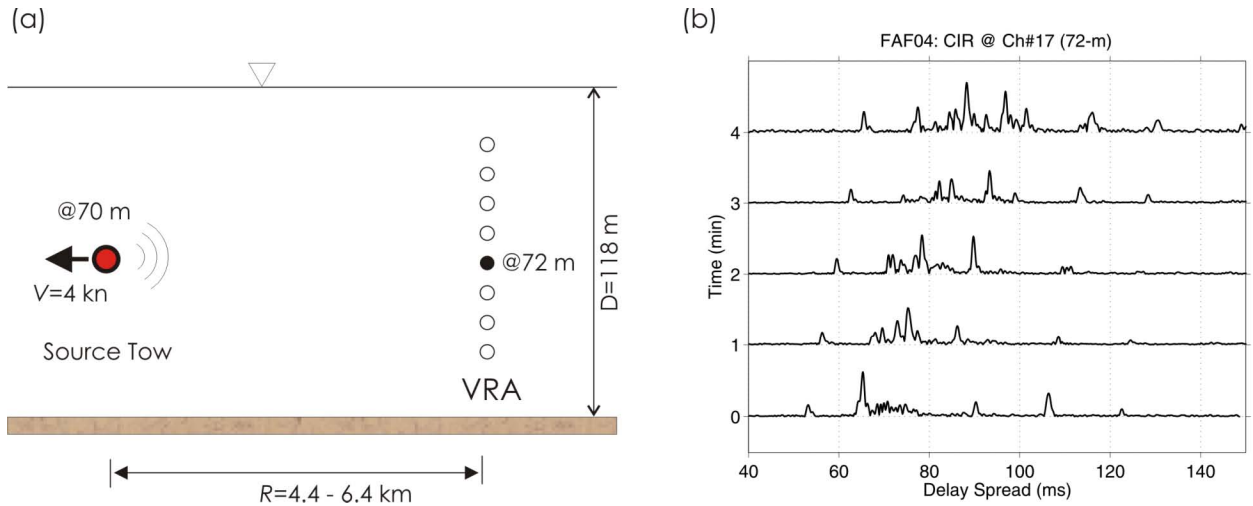
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We have shown that the time reversal approach provides nearly optimal performance in conjunction with channel equalization [2-6]. The benefit of the time reversal approach is lower computational complexity for two reasons. First, multiple receiver elements are combined into a single channel and thus the complexity of successive channel equalizers remains unchanged as the number of receive elements increases. Second, the number of taps required for an equalizer is much smaller than the number of symbols spanning the channel delay spread due to the temporal compression provided by time reversal combining.

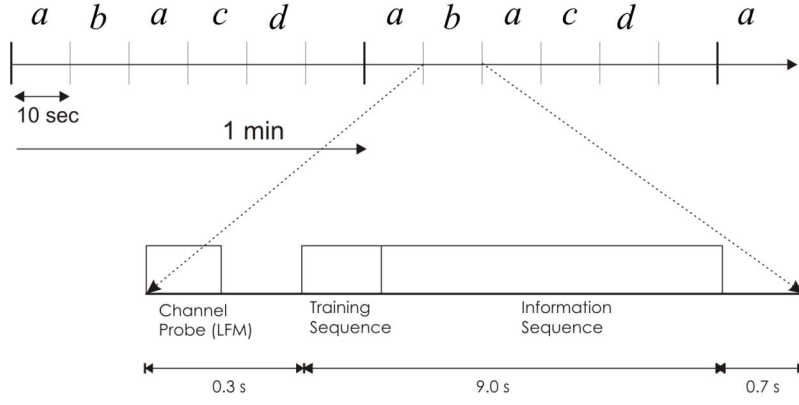
Time reversal, however, normally assumes that the channel is time-invariant (or slowly-varying) while the channel actually continues to evolve over time in a fluctuating ocean environment, resulting in a mismatch between the measured channel responses and the actual channel responses. This is especially true in the presence of source motion due to coupling of space (different source position) and time (temporal variation). To accommodate the channel variations, the channel can be frequently updated using previously detected symbols, prior to multi-channel (or diversity) combining [7-8] (see Fig. 4(b)).

## WORK COMPLETED

Based on the results reported in [1], we advanced our understanding of SAC by conducting a follow-up experiment (FAF-04) in the 2-4 kHz frequency band that includes: (i) binary-phase shift keying (BPSK) coherent modulation, (ii) radial motion (significant Doppler), and (iii) signal design suitable for SAC (interleaving, see Fig. 2). The schematic of SAC is illustrated in Fig. 1. The source was suspended from the R/V Alliance at 70-m depth moving at 4 kts away from the moored VRA such that the virtual horizontal array is end-fire (as viewed from above) as opposed to the broadside aperture generated in [1].



**Figure 1. (a) Schematic of a synthetic aperture time reversal communication between a towed source at about 4 kts and a fixed receiver at 72-m depth. (b) The first five channel impulse responses (envelope) spaced 1-min (~120 m) apart.**



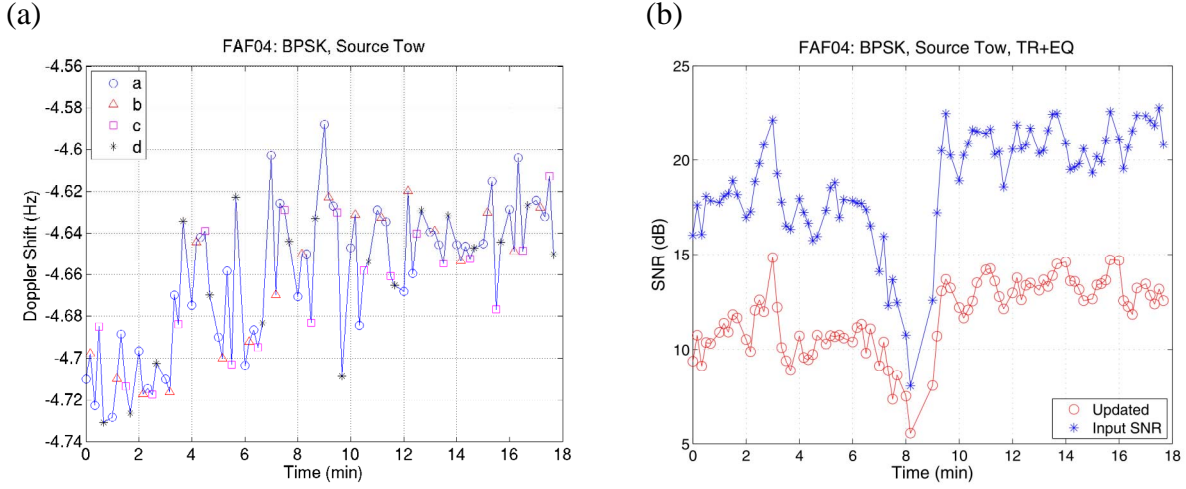
**Figure 2.** *Communication signals transmitted by a probe source during the SAC experiment. Each 10-sec data packet denoted by letters  $\{a, b, c, d\}$  consists of a channel probe (LFM) followed by a 9-sec communication sequence. Five data packets in the order  $\{a, b, a, c, d\}$  are concatenated together to form a single 50-sec long communication sequence. The 50-sec long signal then was repeated every minute from the towed source during the 18-min run.*

## RESULTS

We analyzed the data collected during the 18-min-long source tow data on JD199 where the source range increased from 4.4 km to 6.4 km. The detailed structure of the transmitted signal is shown in Fig. 2. Each sequence can be treated either independently or combined coherently for the SAC. The first five channel impulse responses spaced 1-min apart ( $\sim 120$ -m) are shown in Fig. 1(b). The symbol rate was 1 ksymbols/s using BPSK modulation with a 2-4 kHz bandwidth centered at 3 kHz.

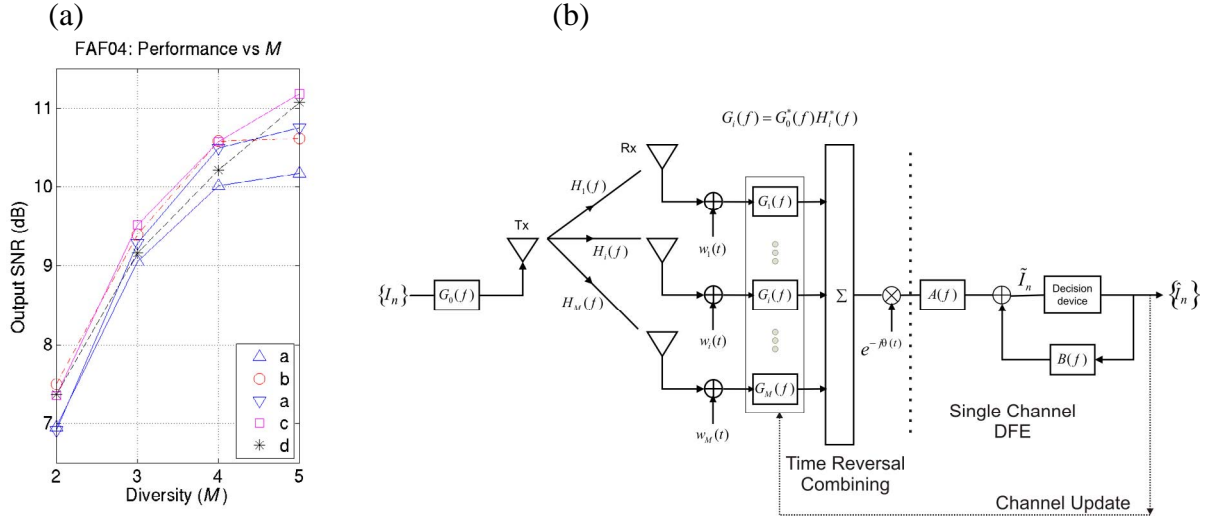
Doppler compensation involves initial estimation of Doppler shift followed by resampling to compensate for either compression or expansion of the received broadband signals. To estimate the Doppler shift, we track the initial phase at the carrier frequency 3 kHz using a decision-feedback carrier phase estimate based on the maximum likelihood criterion whose slope corresponds to the average Doppler shift. The resulting estimate of the Doppler shifts is shown in Fig. 3(a). The time-varying Doppler shift is around -4.65 Hz with a general decreasing trend in magnitude over time. A constant Doppler shift is assumed within each 10-sec transmission and the residual Doppler shift is compensated by a phase tracking algorithm in the demodulation process. To resample the received waveform, we use a combination of efficient polyphase filters and linear interpolation on the complex baseband signal.

The performance of each single transmission/reception over the 18-min observation interval (circles) is displayed in Fig. 3(b). Note that the output SNR closely follows the input SNR. Due mostly to the high input SNR (i.e., 15-25 dB), even single receptions alone provide good performance. To explore SAC, we added ambient noise separately observed during the experiment to the individual receptions such that the input SNR is lowered to approximately 3 dB and a single transmission/reception alone provides poor performance (e.g., 0 dB).



**Figure 3. (a) Estimate of the individual Doppler shifts due to source motion during the 18-min-long source-tow run. The sequence of data packets is consistent with Fig. 2. (b) Performance of single channel SAC in terms of output SNR. The input SNR (\*) is displayed as a reference.**

Figure 4(a) demonstrates that the overall performance is improved significantly especially when two ( $M=2$ ) or three ( $M=3$ ) transmissions are combined together.



**Figure 4. (a) Performance of synthetic aperture communications versus the number of transmissions combined ( $M$ ) spaced 1-min apart as shown in Fig. 2 for five different data streams. Ambient noise is added to the individual receptions in order to bring the input SNR down to approximately 3 dB such that a single transmission alone provides poor performance. (b) Block diagram for time reversal diversity-combining followed by a single channel DFE, with frequent channel updates using previously detected symbols.**

## IMPACT/APPLICATIONS

While our understanding of underwater acoustic communications has improved over the last two decades [9], communications involving mobile assets (e.g., gliders and AUVs) remains quite challenging. First, slow propagation speed of acoustic waves makes Doppler effects significant even for a relatively slow-moving platform. Moreover, the Doppler shift is time varying and the temporal variability of underwater channels induces additional Doppler spreading (i.e., time-selective fading). Second, underwater acoustic systems typically operate at low SNR and thus require diversity (e.g. array) to enhance the SNR and mitigate the channel fading effect.

In spite of its practical significance, however, [1] is believed to be the first paper to investigate SAC between a single transmitter and a receiver in shallow water, exploiting the relative motion between the two over a 5-km range. Here the SAC is extended in three respects: (1) coherent communications is demonstrated using BPSK modulation, (2) significant Doppler due to radial motion is mitigated, and (3) time reversal with channel updates is implemented to accommodate the time-varying channel impulse responses. Two to five consecutive transmissions from a source moving at 4 kts are combined successfully after Doppler compensation, confirming the feasibility of coherent synthetic aperture communications using time reversal.

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